

# NMSSM neutralino dark matter

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**Abstract.** We study the viability of the lightest neutralino as a dark matter candidate in the Next-to-Minimal Supersymmetric Standard Model. Taking into account accelerator constraints as well as bounds on low-energy observables, and imposing consistency with present bounds on the neutralino relic density, we address the prospects for the direct detection of neutralino dark matter. We find regions of the allowed parameter space where the neutralino detection cross section is within the reach of dark matter detectors, essentially owing to the presence of very light singlet-like Higgses, and to either singlino dominated or very light neutralinos.

**Keywords:** Dark Matter, Supersymmetry Phenomenology, Cosmology of Theories beyond the SM

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The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is a well-motivated extension of the Minimal Supersymmetric Standard Model (MSSM) by a singlet superfield  $\hat{S}$ . In addition to providing an elegant solution to the so-called  $\mu$  problem of the MSSM, and rendering the Higgs “little fine tuning problem” of the MSSM less severe, the presence of additional fields (CP-even, CP-odd neutral Higgs bosons, and a fifth neutralino) leads to a richer and more complex phenomenology. In the NMSSM, one has possibility of dark matter scenarios that can be very different from those encountered in the MSSM, both regarding the relic density as well as prospects for direct detection. In particular, the exchange of very light Higgses can lead to large direct detection cross sections, within the reach of the present generation of dark matter detectors [1, 2].

The NMSSM superpotential contains new couplings, involving the Higgs doublets and the singlet,

$$W_{\text{NMSSM}} = \epsilon_{ij} \left( Y_u \hat{H}_2^j \hat{Q}^i \hat{u} + Y_d \hat{H}_1^i \hat{Q}^j \hat{d} + Y_e \hat{H}_1^i \hat{L}^j \hat{e} \right) - \epsilon_{ij} \lambda \hat{S} \hat{H}_1^i \hat{H}_2^j + \frac{1}{3} \kappa \hat{S}^3. \quad (1)$$

New terms associated with additional soft supersymmetry (SUSY) breaking trilinear couplings  $A_\lambda$  and  $A_\kappa$  will also appear in the Lagrangian. After the spontaneous breaking of electroweak (EW) symmetry, the neutral Higgs scalars develop vacuum expectation values (VEVs),  $\langle H_1^0 \rangle = v_1$ ,  $\langle H_2^0 \rangle = v_2$  and  $\langle S \rangle = s$ . This leads to the dynamical generation of an effective interaction  $\mu \hat{H}_1 \hat{H}_2$ , with  $\mu \equiv \lambda s$ . In the NMSSM spectrum, we now have three CP-even and two CP-odd Higgs states. In particular, the lightest Higgs scalar can be written as  $h_1^0 = S_{11} H_1^0 + S_{12} H_2^0 + S_{13} S$ , where  $S$  is the unitary matrix that diagonalises the  $3 \times 3$  scalar Higgs mass matrix. In the neutralino sector, the singlino mixes with the bino, wino and Higgsinos. The lightest state can be now expressed as  $\tilde{\chi}_1^0 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}_3^0 + N_{13} \tilde{H}_1^0 + N_{14} \tilde{H}_2^0 + N_{15} \tilde{S}$ , where  $N$  diagonalises the  $5 \times 5$  neutralino mass matrix.

The low-energy NMSSM parameter space can be described in terms of the  $\lambda, \kappa, \tan\beta, \mu, A_\lambda, A_\kappa$  degrees of freedom, as well as the soft SUSY-breaking terms, namely gaugino masses,  $M_{1,2,3}$ . A thorough analysis of the low-energy NMSSM phenomenology (minimisation of the potential, computation of spectrum and compatibility with LEP/Tevatron bounds) can be obtained using the NMHDECAY 2.0 code [3]. Additionally, we have also included in our analysis [2] a more precise computation of the  $b \rightarrow s\gamma$  decay in the NMSSM [4], taking into account next-to-leading order contributions, and imposing consistency at the  $2\sigma$  level with the experimental central value [5],  $\text{BR}^{\text{exp}}(b \rightarrow s\gamma) = (3.55 \pm 0.27) \times 10^{-4}$ . Likewise, we have also incorporated the constraints coming from the contribution of a light pseudoscalar  $a^0$  in the NMSSM to the rare  $B$ - and  $K$ -meson decays [4]. Finally, in our analysis we have also included the constraints coming from the SUSY contributions to the muon anomalous magnetic moment,  $a_\mu = (g_\mu - 2)$ . At present, the observed excess in  $a_\mu^{\text{exp}}$  [6] constrains a possible SUSY contribution to be [7]  $a_\mu^{\text{SUSY}} = (27.6 \pm 8) \times 10^{-10}$ .

As thoroughly discussed in [1, 2], an extensive part of the low-energy NMSSM parameter space is directly excluded on theoretical grounds, namely the occurrence of tachyons. Moreover, false minima, and Landau poles for the couplings in  $W_{\text{NMSSM}}$  also render unviable further areas. In regions surviving the latter constraints and the LEP/Tevatron bounds, and that present the most appealing prospects regarding dark matter direct detection, an important role is played by the  $b \rightarrow s\gamma$  decay, which can in principle exclude important regions of the parameter space (due to very large contributions to  $\text{BR}(b \rightarrow s\gamma)$  from charged Higgs exchange). Concerning the SUSY contributions to  $a_\mu$ , in the dark-matter interesting regions, these tend to be in general quite small. A sufficiently large  $a_\mu^{\text{SUSY}}$  can nevertheless be obtained when slepton (and gaugino) masses are decreased, in association with large values of the slepton trilinear couplings.

In order to be a good dark matter candidate, the lightest NMSSM neutralino must also comply with the increasingly stringent bounds on its relic density,

$$0.1 \lesssim \Omega h^2 \lesssim 0.3 \text{ (astrophysical)}, \quad 0.095 \lesssim \Omega h^2 \lesssim 0.112 \text{ (WMAP)}, \quad (2)$$

respectively arising from astrophysical constraints [8], and from taking into account the recent three years data from the WMAP satellite [9].

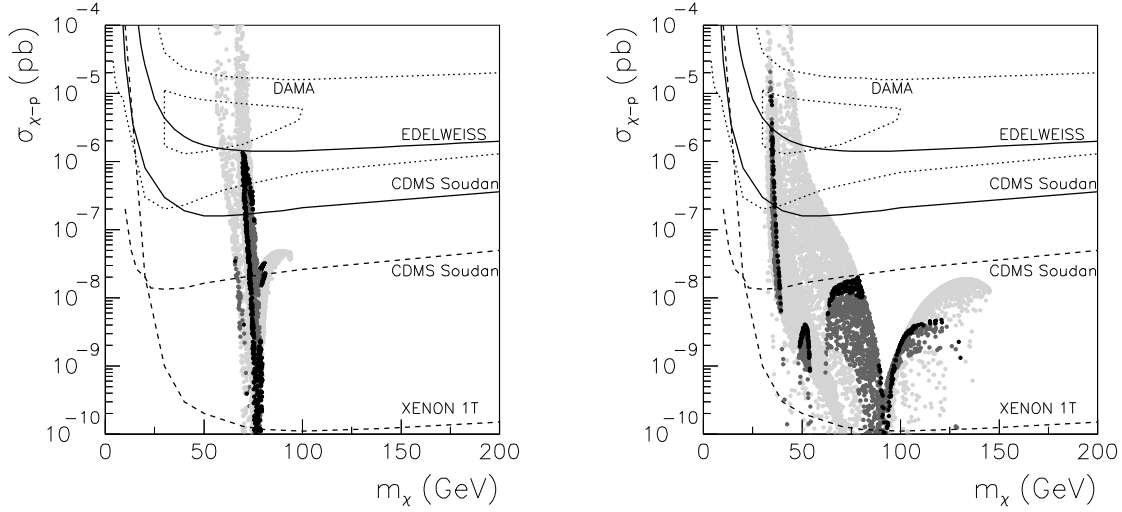
Compared to the MSSM, there are several alterations leading to  $\Omega_{\tilde{\chi}_1^0} h^2$ : first, the possibility of a singlino-like lightest supersymmetric particle (LSP), associated with new couplings in the interaction Lagrangian, may favour the coupling of WIMPs to a singlet-like Higgs, whose mass can be substantially lighter than in the MSSM, given the more relaxed experimental constraints. Secondly, in the NMSSM we have new open channels for neutralino annihilation, e.g.  $s$ -channel resonances, new channels with annihilation into  $Z h_1^0$ ,  $h_1^0 h_1^0$ ,  $h_1^0 a_1^0$  and  $a_1^0 a_1^0$  (due to light  $h_1^0$  and  $a_1^0$  states), providing important contributions to the annihilation and co-annihilation cross-sections [10]. In our analysis [2], the results for the neutralino relic density, obtained from an NMHDECAY link to MicrOMEGAS [10].

In the regions of the parameter space likely to have large neutralino detection cross sections [1], we have found that, in general, the correct relic density can only be obtained when either the singlino composition of the neutralino is large enough or when the annihilation channels into  $Z$ ,  $W$ , or  $h_1^0$  are kinematically forbidden. Interestingly, some

allowed areas were very close to the tachyonic border, which as we verified, can give rise to very large direct detection cross sections.

As pointed out in [1], the existence of a fifth neutralino state, together with the presence of new terms in the Higgs-neutralino-neutralino interaction (which are proportional to  $\tilde{\lambda}$  and  $\kappa$ ), trigger new contributions to the spin-independent part of the neutralino-nucleon cross section,  $\sigma_{\tilde{\chi}_1^0-p}$ . On the one hand, although the term associated with the  $s$ -channel squark exchange is formally identical to the MSSM case, it can be significantly reduced if the lightest neutralino has a major singlino composition. On the other hand, and more importantly, the dominant contribution to  $\sigma_{\tilde{\chi}_1^0-p}$ , associated to the exchange of CP-even Higgs bosons on the  $t$ -channel, can be largely enhanced when these are very light. Consequently, large detection cross sections can be obtained, even within the reach of the present generation of dark matter detectors.

As illustrative examples of our analysis, let us consider two cases, which represent the most relevant features of NMSSM dark matter scenarios. Let us begin by considering  $M_1 = 160$  GeV,  $A_\lambda = 400$  GeV,  $A_\kappa = -200$  GeV, and  $\mu = 130$  GeV, with  $\tan\beta = 5$ , leading to a parameter space consistent with bounds on  $a_\mu^{\text{SUSY}}$  and  $\text{BR}(b \rightarrow s\gamma)$ . In regions of the parameter space where the neutralino is relatively heavy and has a mixed bino-Higgsino composition, the relic density is too small. As the neutralino mass decreases, some annihilation channels become kinematically forbidden, such as annihilation into a pair of  $Z$  or  $W$  bosons when  $m_{\tilde{\chi}_1^0} < M_Z$  or  $m_{\tilde{\chi}_1^0} < M_W$ , respectively. Below these, the resulting relic density can be large enough to fulfil the WMAP constraint, which occurs for distinct regions in parameter space [2]. One of the allowed regions is close to the tachyonic area and exhibits very light singlet-like Higgses, potentially leading to large detection cross sections. This is indeed the case, as evidenced on the left-hand side of Fig. 1, where the theoretical predictions for  $\sigma_{\tilde{\chi}_1^0-p}$  are plotted versus the lightest neutralino mass. The resulting  $\sigma_{\tilde{\chi}_1^0-p}$  spans several orders of magnitude, but, remarkably, areas with  $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-7}$  pb are found. These correspond to the above mentioned regions of the parameter space with very light singlet-like Higgses ( $25 \text{ GeV} \lesssim m_{h_1^0} \lesssim 50 \text{ GeV}$  with  $S_{13}^2 \gtrsim 0.99$ ). The neutralino is a mixed singlino-Higgsino state ( $N_{15}^2 \approx 0.35$ ) with mass around 75 GeV. The sensitivities of present and projected dark matter experiments are also depicted for comparison. On the right-hand side of Fig. 1 we show the resulting  $\sigma_{\tilde{\chi}_1^0-p}$  when the neutralino composition is changed, namely when the Higgsino component is enhanced. In particular, we consider the choice  $M_1 = 330$  GeV,  $\tan\beta = 5$ ,  $A_\lambda = 570$  GeV,  $A_\kappa = -60$  GeV, with  $\mu = 160$  GeV. Such neutralinos annihilate more efficiently, thus leading to a reduced  $\Omega_{\tilde{\chi}_1^0} h^2$ , so that the astrophysical constraint becomes more stringent. On the right-hand side of Fig. 1, the various resonances appear as funnels in the predicted  $\sigma_{\tilde{\chi}_1^0-p}$  for the regions with the correct  $\Omega_{\tilde{\chi}_1^0} h^2$  at the corresponding values of the neutralino mass ( $m_{\tilde{\chi}_1^0} \approx M_Z/2$  and  $m_{\tilde{\chi}_1^0} \approx m_{h_1^0}/2$ ). Below the resonance with the  $Z$  boson, light neutralinos are obtained  $m_{\tilde{\chi}_1^0} \lesssim M_Z/2$  with a large singlino composition which have the correct relic abundance. The lightest Higgs is also singlet-like and very light, leading to a very large detection cross section,  $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-6}$  pb.



**FIGURE 1.** Scatter plot of the scalar neutralino-nucleon cross section as a function of the lightest neutralino mass. On the left,  $M_1 = 160$  GeV,  $\tan\beta = 5$ ,  $A_\lambda = 400$  GeV,  $A_\kappa = -200$  GeV, and  $\mu = 130$  GeV. All the points represented are in agreement with LEP/Tevatron,  $a_\mu^{\text{SUSY}}$ , and  $\text{BR}(b \rightarrow s\gamma)$  bounds. Dark grey dots represent points which, in addition, fulfil  $0.1 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.3$ , whereas black dots are those in agreement with the WMAP constraint. The sensitivities of present and projected experiments are also depicted, with solid and dashed lines, respectively. On the right, a different example with  $M_1 = 330$  GeV,  $\tan\beta = 5$ ,  $A_\lambda = 570$  GeV,  $A_\kappa = -60$  GeV, with  $\mu = 160$  GeV, a case where the resulting  $a_\mu^{\text{SUSY}}$  is outside the experimental  $2\sigma$  region.

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